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(54) **Adaptive control system having multiple inputs and multiple outputs**

(57) An adaptive control system for controlling a plant (20) has a plurality of actuator means (60) for controlling the plant, a plurality of sensor means (70) for sensing the degree of success in controlling the plant, and actuator control means (41) adapted to control each actuator means (60) in response to selected ones of the sensor means (70), the selected ones being some and not all of the plurality of sensor means (70). The actuator control means (41) selects the selected ones of the sensor means (70) by considering couplings between each actuator means (60) and each sensor means (70) and determining which couplings are the most significant.

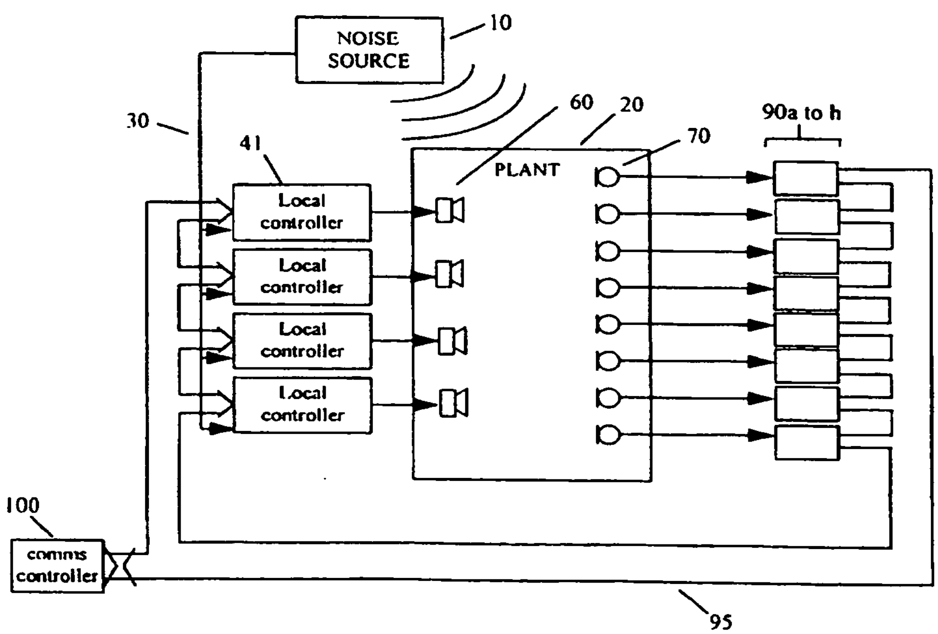

Figure 4

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Prior Art

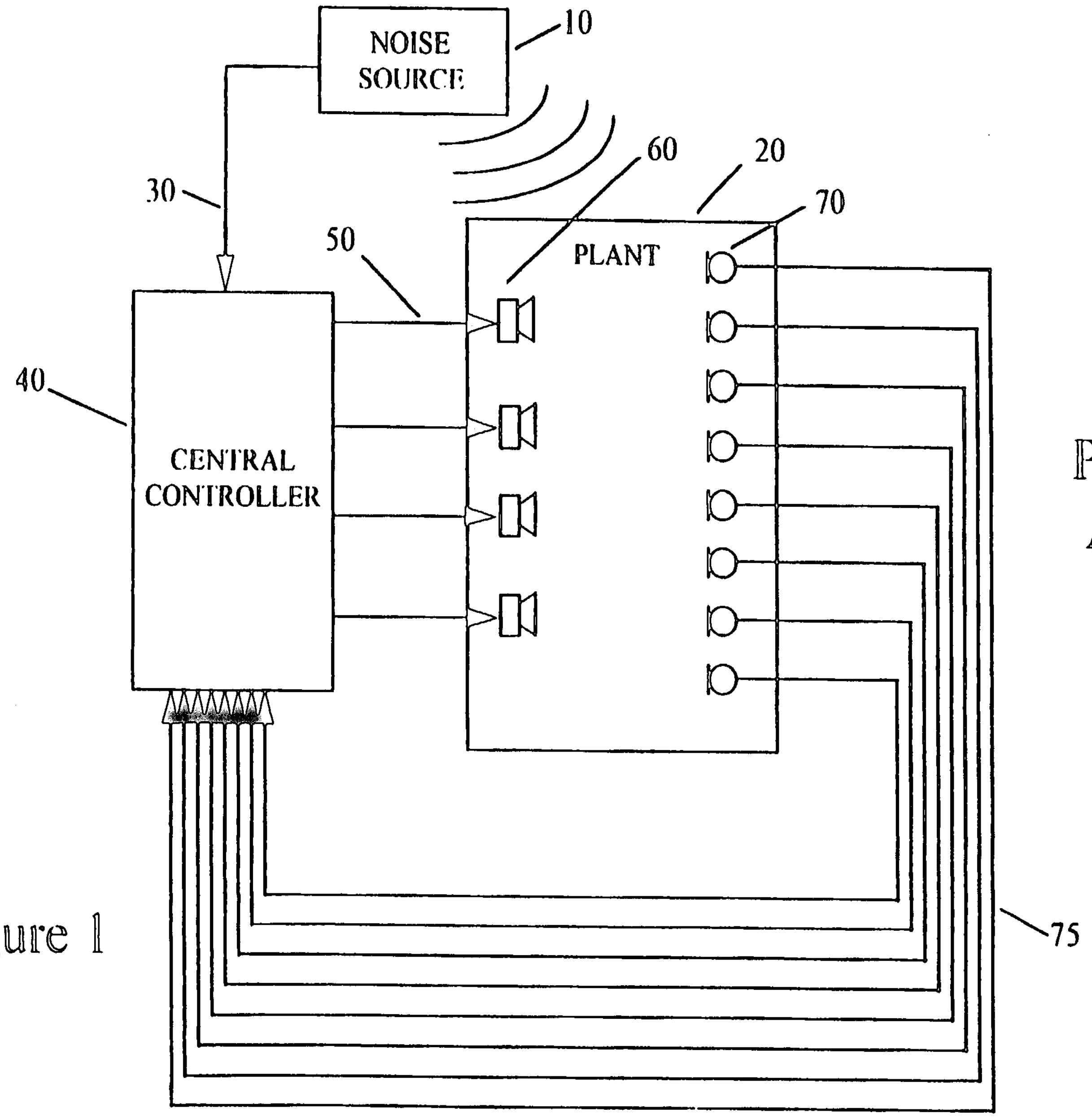
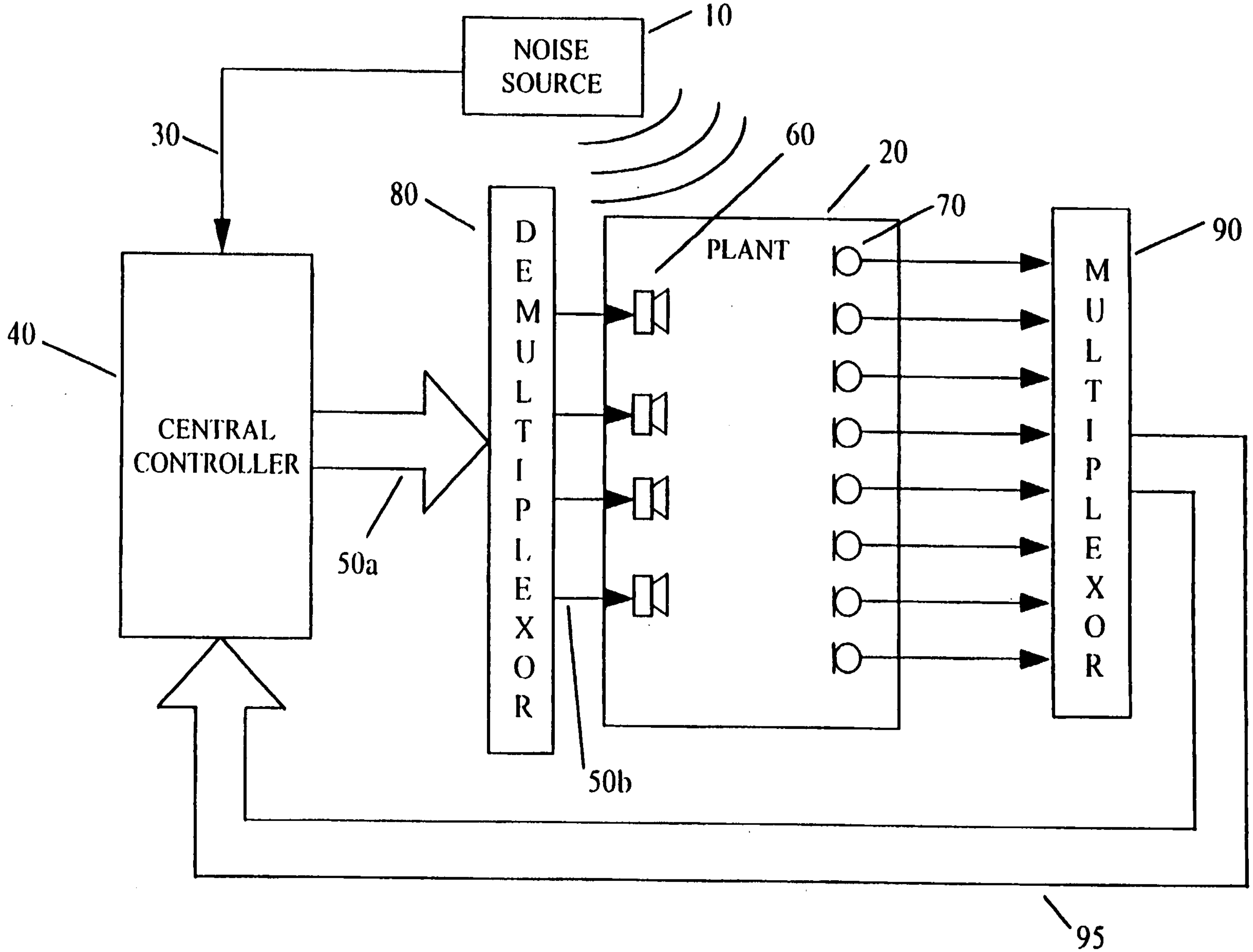


Figure 1



Prior Art

Figure 2

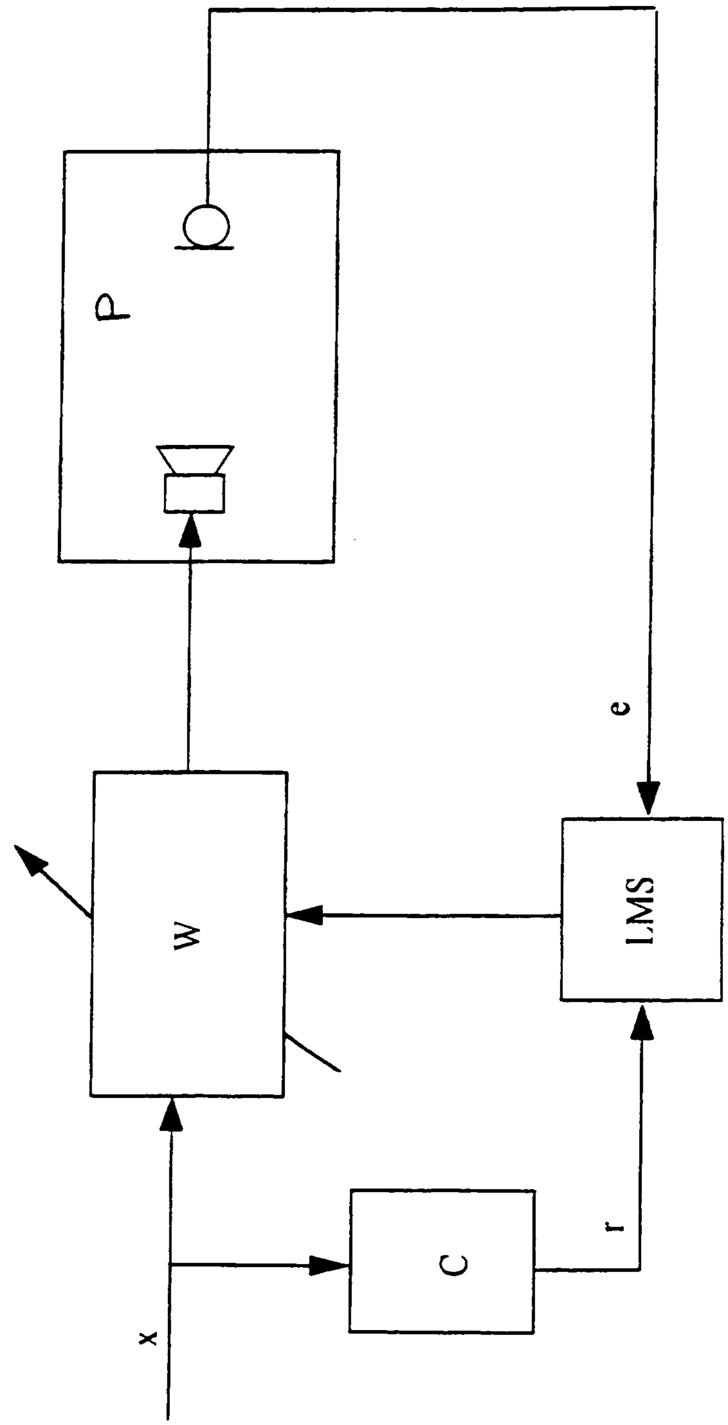
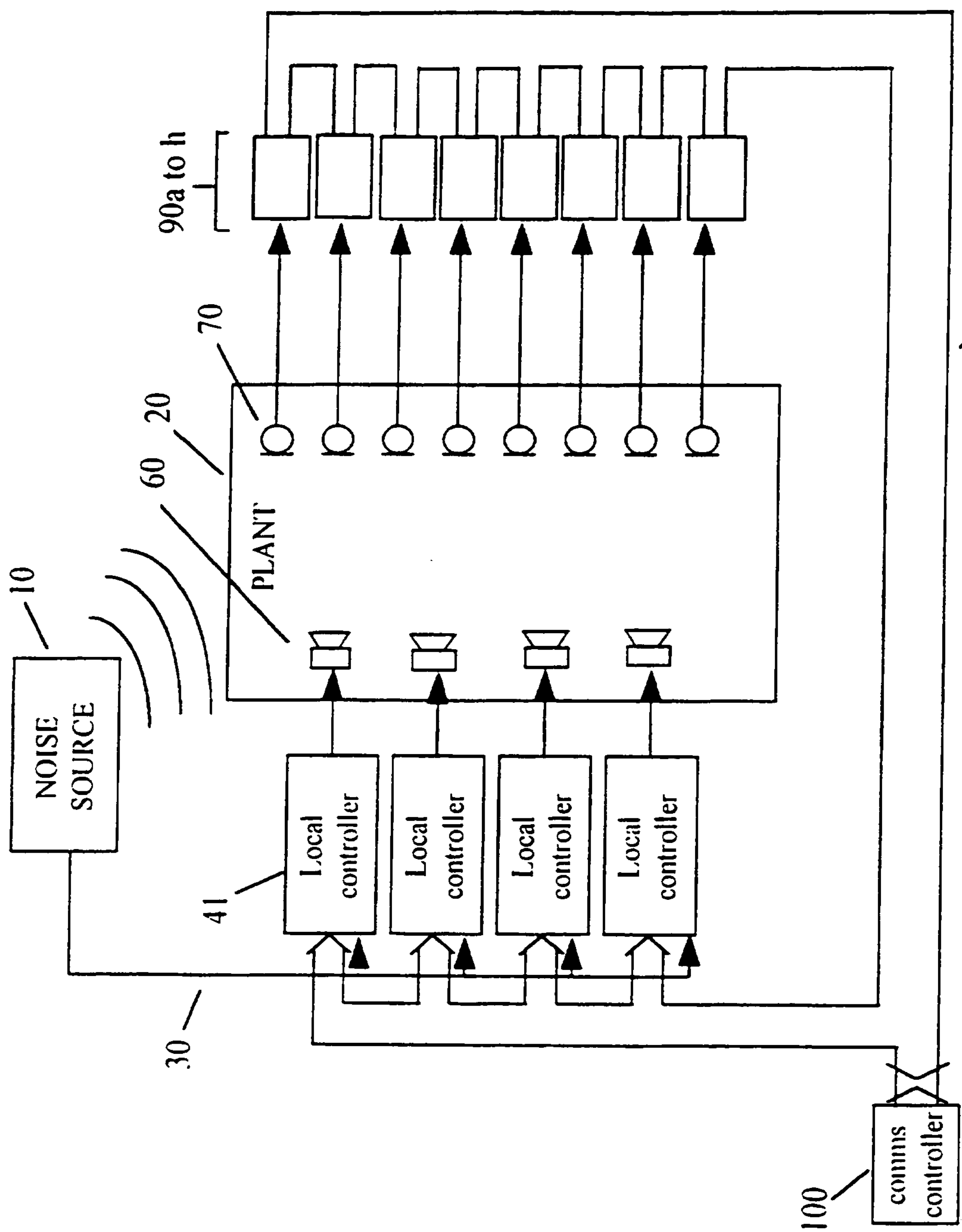


Figure 3



10
NOISE SOURCE
PLANT
20
60
70
90a to h
95
30
41
Local controller
Local controller
Local controller
Local controller
100
comms controller

Figure 4

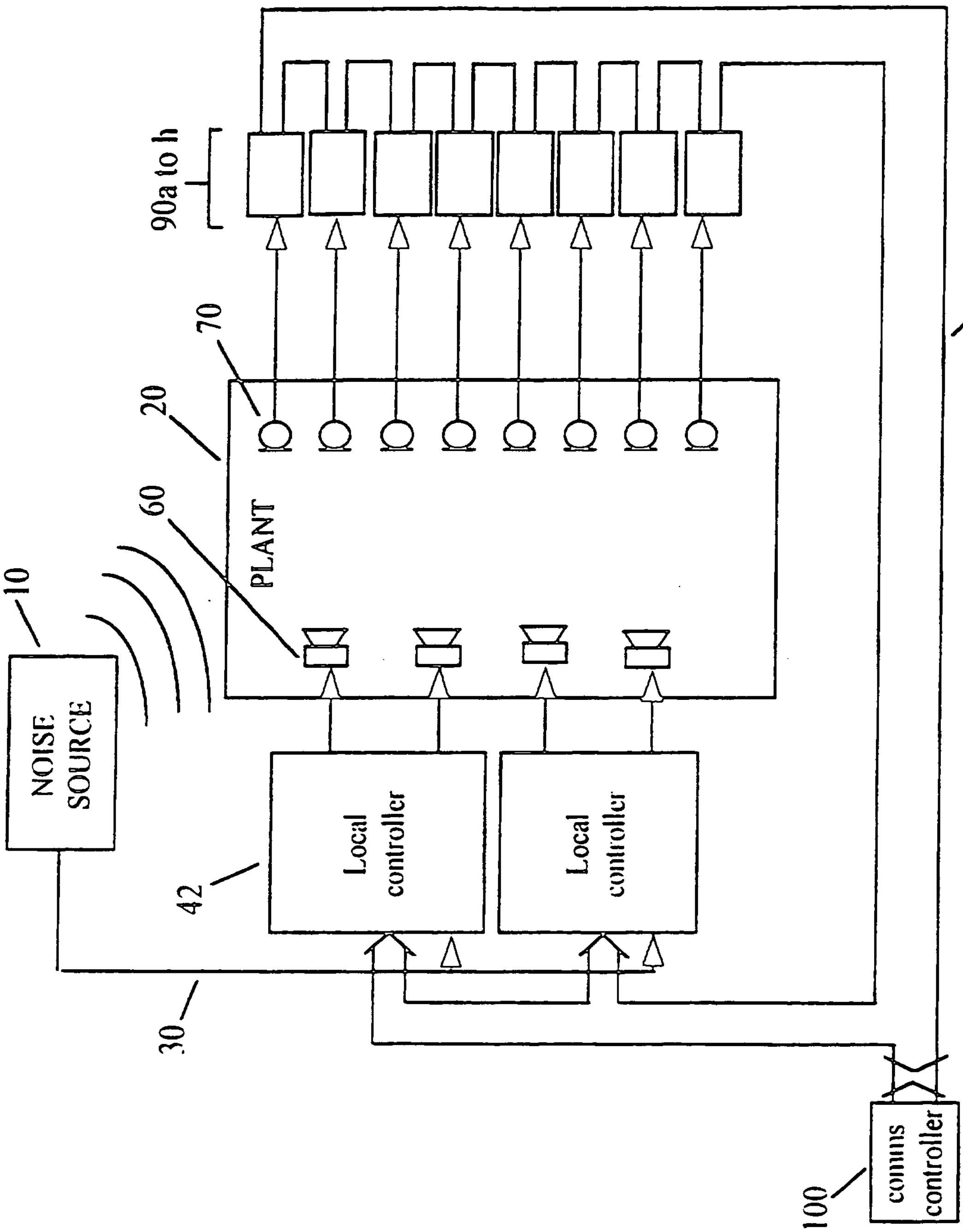

NOISE SOURCE
10
PLANT
20
60
70
90a to h
95
Local controller
Local controller
42
30
comms controller
100

Figure 5

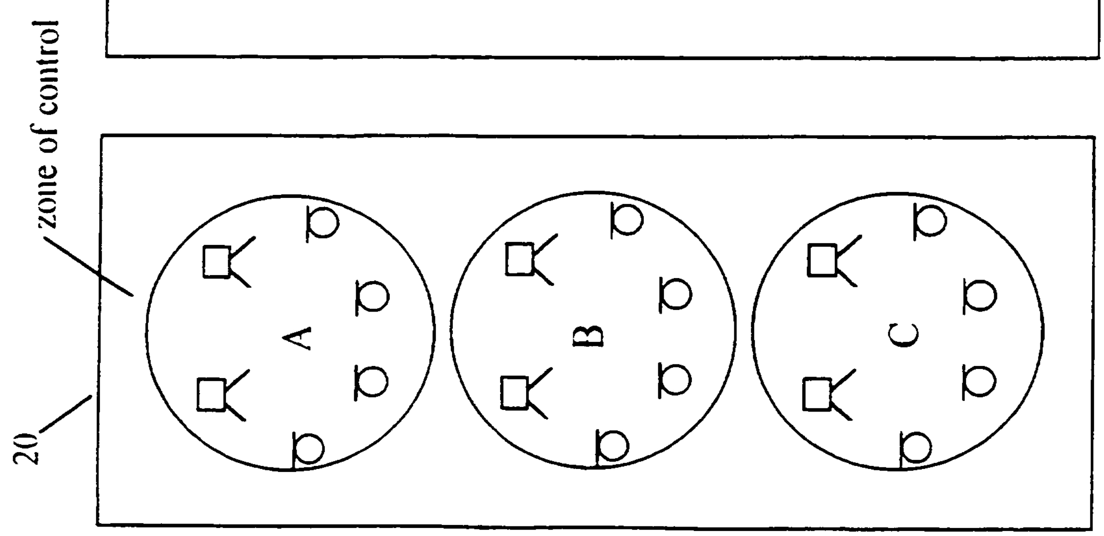


Figure 6a

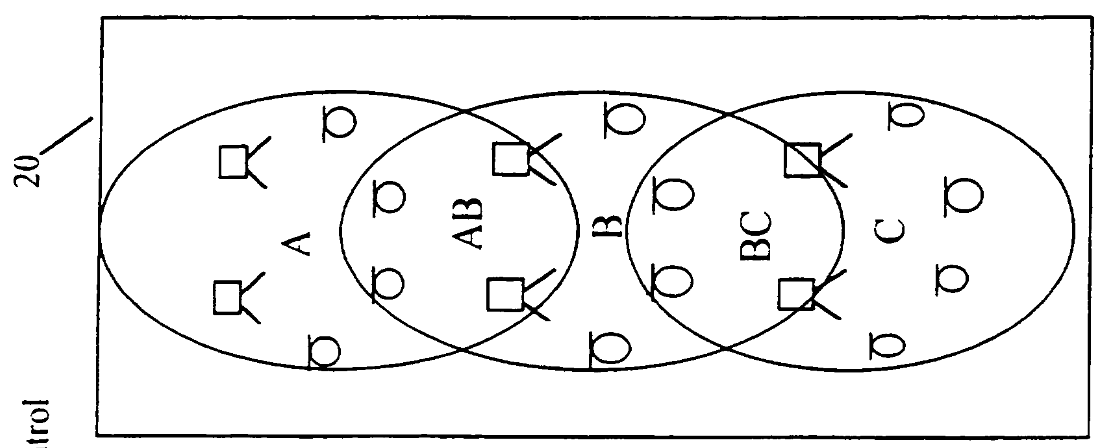


Figure 6b

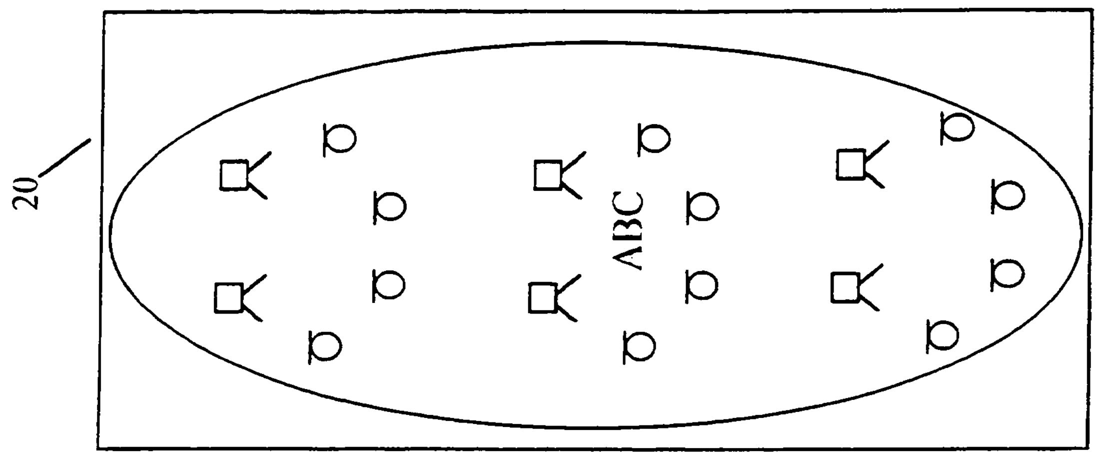


Figure 6c

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REDUCTION OF PROCESSING IN AN ADAPTIVE CONTROL SYSTEM HAVING MULTIPLE INPUTS AND MULTIPLE OUTPUTS

The present invention generally relates to an adaptive control system and a method for controlling a plant which has multiple inputs for controlling the plant and multiple outputs from the plant which are required to be at a desired level.

Hereinafter the term "plant" is used as a control system term to describe a system having multiple inputs and multiple outputs; where each input may effect to some degree each output.

Much work has been done on the development of systems which can adaptively control a plant. One particular area is active acoustic vibration control which is based on the principle of superimposing on undesired disturbances in an acoustic medium forced acoustic waves with equal amplitude and opposite polarity to those of the undesired disturbances (hereinafter the term acoustic vibration encompasses vibration and sound).

One problem which has generated much interest is the cancellation of acoustic vibration in a three-dimensional volume. A simple approach is the use of a single loudspeaker to generate the acoustic waves cancelling the acoustic vibrations and the use of a single sensor to detect the result and adapt the output of the loudspeaker to minimise the resultant acoustic vibrations. This approach which utilises a single path feedback arrangement, can only generate a very localised volume of control.

This approach was further developed in WO89/11841 for use in conjunction with a seat in a vehicle. In this arrangement two loudspeakers generate cancelling

sound to generate a quiet zone around the head of the occupant of a seat. Two error microphones are used as a feedback to a controller to control the output to the loudspeakers. This arrangement is designed for use in vehicles such as aircraft wherein a large number of seats are provided. The controller is designed to operate independently and it is assumed that there is no interference from any adjacent seats. This system therefore comprises a fully decoupled active control system where multiple independent controllers are provided within a volume, e.g. the cabin of an aircraft.

The stability of such fully decoupled systems has been explored by S.J. Elliott and D.C. Boucher. These workers found that a fully decoupled control system in which a number of controllers are implemented independently, can be stable under certain criteria. It is acknowledged in this paper that such decentralised architectures could be used to efficiently implement adaptive multichannel feedforward active sound control systems only under certain limited conditions required for stability.

The other approach to the active control acoustic vibration is the fully centralised multiple input multiple output control system such as disclosed in EP-A-0285632. What is disclosed in this document is an active control system for controlling acoustic vibration based on the filtered-x least mean square (LMS) algorithm. The basic layout of two alternative such systems are illustrated in Figures 1 and 2 herein.

As can be seen in Figure 1, a source of undesired acoustic noise 10 transmits undesired acoustic vibration into a plant 20, e.g. the cabin of a vehicle. Such a noise source can for instance be one

or more engines which propel the vehicle or in a road vehicle, vibrations generated by the wheels on the road. It is thus desirable to reduce this undesired noise within the plant 20.

A reference signal 30 is obtained from the noise source. If the noise source 10 is an engine this can either be a rotational transducer or an electric transducer. Where the noise source is a wheel, the reference signal 30 can be obtained from a motion sensor, e.g. an accelerometer on the hub of the wheel.

The reference signal 30 provides a feedforward signal which is input into a central controller 40. The central controller 40 is programmed to operate in accordance with the filtered-x LMS algorithm to generate a number of output signals 50 (in the illustrated case, 4) to be input to the plant 20. The signals 50 are input into loudspeakers 60 positioned within the plant to generate cancelling sound. Also positioned within the plant 20 are sensors in the form of error microphones 70 to detect the residual sound within the plant 20. The signals (error signals) from the microphones 70 are fed back to the central controller 40 by wires 75 for the adaption of the output signals 50 in order to reduce the residual sound and vibration within the plant 20.

Figure 2 illustrates an alternative arrangement to that of Figure 1 wherein the error signals from the microphones 70 are multiplexed by a multiplexer 90. The output signals on lines 95 from the multiplexer 90 are input to the central controller 40. Within the central controller 40 the filtered-x LMS algorithm operates to generate multiplexed output signals 50a which are demultiplexed by the demultiplexer 80. The output signals 50b from the demultiplexer are then fed to the loudspeakers 60 in the plant 20.

This arrangement reduces the wiring necessary between a plant and the central controller.

In the fully coupled multiple input multiple output control system, when there are a large number of inputs, e.g. loudspeakers, and a large number of outputs, e.g. microphones, the processing requirements become large. The present inventors have realised that it is possible to reduce the processing requirements of a multiple input, multiple output control system without resorting to the use of a fully decoupled system. The present inventors have realised that it is possible to reduce the processing requirements of a multiple input, multiple output control system since not all outputs may be significantly affected by each input. If the significance of the coupling between an input and an output is low, it can be ignored without affecting the stability of the control system.

The present invention provides an adaptive control system for controlling a plant comprising a plurality of actuator means for controlling said plant; a plurality of sensor means for sensing the degree of success in controlling said plant; and actuator control means adapted to control each said actuator means in response to selected ones of said plurality of sensor means, said selected ones being some and not all of said plurality of sensor means, said actuator control means being adapted to select said selected ones of said sensor means by considering couplings between each said actuator means and each said sensor means and then determining which couplings are the most significant.

Thus, in accordance with the present invention the processing requirements of an adaptive control system of a plant can be reduced by learning which of

the couplings between the inputs and outputs to the plant are significant and affect the stability of the control system.

The present invention is preferably suited for use with a feedforward control system wherein reference means is provided to give an indication of at least one parameter of the phenomenon affecting the plant, and the actuator control means is responsive to the reference means to control the plant.

Conveniently, in order for the actuator control means to determine which of the couplings are most significant, test signal generating means is provided for generating a test signal for each of the actuator means. The actuator control means is able to determine the most significant couplings of the sensor means with each of the actuator means by comparing the responses of each of the sensor means to the test signal for each of the actuator means.

This learning of the responses can take place either during an initialisation phase of the system or continuously during the operation of the system. Where responses are learnt continuously during the operation of the system, conveniently continuous test generating means is provided to generate a test signal uncorrelated with any phenomenon affecting the plant for each of the actuator means.

One method of determining which couplings are most significant is by monitoring the real part of an eigenvalue of a matrix derived from the responses of each of the sensor means to each of the actuator means. Conveniently the derived matrix is

$(C_s^H C_s + \beta I)$ where

H denotes the complex conjugate of the transposed matrix,

β is a weighting coefficient,

C_s is a matrix of responses of selected sensor means to selected actuator means (i.e. C_s is a modified version of C with some of the terms in C set to zero; C being a matrix of the responses of each of the sensor means to each of the actuator means),

I is the identity matrix.

The term βI is used to give effort weighting in the control system and makes the eigenvalues of the matrix $(C_s^H C_s + \beta I)$ more positive. When the real parts of the eigenvalues of $(C_s^H C_s + \beta I)$ are positive then the control system is convergent and the greater the magnitude of the positive eigenvalue the greater is the rate of convergence. If the real parts of the eigenvalues of the matrix $(C_s^H C_s + \beta I)$ are negative then the control system is divergent and unstable.

The most significant couplings between actuator means and sensor means can be determined by systematically setting to zero terms of the matrix C to form successive matrices C_s and then determining the effect on the real parts of the eigenvalues of the matrix $(C_s^H C_s + \beta I)$. As long as the eigenvalues remain positive and of a sufficient magnitude after a term or terms in C has been set to zero then the term or terms can be replaced by a zero. If the real parts of the eigenvalues of $(C_s^H C_s + \beta I)$ become negative or fall below a certain positive value then it is clear that the term or terms in C is/are a significant term or terms and cannot be set to zero. To speed the process initially, a number of terms in the matrix C can initially be set to zero to form an initial C_s by noting the terms of the least magnitude and then setting them to zero.

Whilst the present invention can be used with a centralised controller such as used in the prior art for instance in Figures 1 and 2, in order to reduce

the processing requirements of the centralised controller, the present invention is particularly suited to the use of distributed processing. A local controller can control one or more actuator means and must be able to receive signals from all of the sensor means (although some of these will be ignored since they are determined to be insignificant). Such distributed processing allows for the control system to be constructed in a modular manner. For instance, a local controller may control a single actuator means and be responsive to eight sensor means. Four other such local controllers can be provided, each of which are connected to the sensor means by a common communication link. If the number of sensor means needs to be increased or decreased, the number of sensor means connected to the communication link is changed and the local controllers must relearn which of the couplings between the sensor means and the actuators are the most significant.

In a modular format, the control system can be considered to comprise a number of local controllers with their own inputs and outputs, e.g. two actuator means and four sensor means. If the system were fully decoupled, each of the local controllers would act independently to its neighbours. In a fully coupled system each local actuator would need to consider the outputs from the sensor means of all of the other modules. In the present invention each of the local controllers needs to take into consideration the output signals of the sensor means of the most closely coupled sensor means to the local controllers actuator means. In a simple form the modular system can be thought of as comprising coupling between nearest neighbour modules, although in a plant which has a complex response, this can be a great over-

simplification.

In modular systems in order to facilitate communication between modules, conveniently each local controller is connected to each sensor means by a communication link over which signals from the sensor means are transmitted in a multiplexed manner. The multiplexing can be achieved using any conventional multiplexing protocols such as time division multiplexing or frequency multiplexing. This allows for the local controllers to select which of the signals from the sensor means it is required to use in the adaption of the output signals to the actuator means. Such a multiplex communication link can either be by wire or by some other wireless communication link, e.g. RF signals or infrared signals.

The present invention is particularly suited for a control system operating the filtered-x least means square (LMS) algorithm or its equivalent the filtered error LMS algorithm such as disclosed in EP-A-0285632, GB-A-2287851, WO94/09482, GB 2271908 and co-pending application number GB-A-2293898 (the content and disclosure of these being hereby incorporated by reference).

In the filtered-x or filtered error LMS algorithms, which can operate either in the time or frequency domains, the LMS algorithm requires either the reference signal or the error signal from the sensors to be filtered by a model filter which models the response of each of the sensor means to an output of each of the actuator means. In the fully coupled filtered-x (filtered reference signal) and filtered error LMS algorithms the model filter must contain all of the responses, i.e. all of the couplings, and the reference signal or the error signal must be filtered thereby.

In an embodiment of the present invention which utilises the filtered-x (filtered reference signal) or filtered error LMS algorithm, the number of values in the model filter are reduced by ignoring the couplings between sensor means and actuator means which are insignificant and do not affect the stability of the control system.

In a fully coupled filtered-x (filtered reference signal) or filtered error LMS algorithm for controlling a system having L sensor means and M actuator means, where the response of a sensor means to an actuator means is represented by J coefficients, the model filter has L x M x J coefficients. In an acoustic system for instance the acoustic response may provide J = 30. For a large active control system the use in for example an aircraft, there could be 100 actuator means and 200 sensor means. Clearly with a system of this size the processing requirements become vast.

In the above example the model filter can be expressed as an L x M matrix. In a fully decoupled system only the diagonal components of such a matrix are required. In the present invention selected components of the matrix are used and these are selected by determining whether these are significant couplings by monitoring the real parts of eigenvalues of a matrix derived from the model filter matrix C.

The determination of the most significant coupling between the actuator means and the sensor means in a control system is dependent upon the stability of the plant. If the plant is stable, once the significant couplings have been determined, it can be assumed that these do not change. Thus, the significant couplings can be learnt during for instance an initialisation phase.

If however the conditions in the plant change during operation of the control system, the selection of the significant couplings made initially may no longer be valid. Under such conditions it is necessary to continuously monitor the responses of the sensor means to the actuator means in order to continuously update the selection of the most significant couplings. This can be achieved by continuously learning the responses by for instance injecting a test signal into the plant which is then correlated with the phenomena to be controlled. Such a continuous learning technique is disclosed in EP-A-0233717 and GB-A-2271909.

Where the control system is used for controlling a plant in response to a disturbance or phenomena comprising selected frequencies or a selected frequency band, preferably the control system operates in the frequency domain in accordance with frequency domain filtered-x (filtered reference signal) or filtered error LMS algorithm. The low level test signal which is injected into the plant continuously during the operation of the control system is used to adapt and learn the model filter coefficients only at frequencies at which the plant is not being controlled. In the filtered-x (filtered reference signal) or filtered error LMS algorithm this avoids the problem of the simultaneous adaption of the model filter coefficients (C) and the digital FIR filter (W) coefficients which can lead to instability or errors.

Embodiments of the present invention will now be described with reference to the accompanying drawings, in which:-

Figure 1 illustrates a multiple input multiple output control system in accordance with the prior art;

Figure 2 illustrates an alternative multiple input multiple output control system in accordance with the prior art;

Figure 3 is a schematic drawing of the time domain filtered-x LMS algorithm;

Figure 4 illustrates a modular control system in accordance with one embodiment of the present invention;

Figure 5 illustrates an alternative modular control system in accordance with one embodiment of the present invention;

Figure 6a illustrates schematically a fully decoupled control system having three separate control zones, each having two loudspeakers and four microphones;

Figure 6b illustrates a partially coupled control system with three control zones A, B and C each having two loudspeakers and four microphones, with zones AB and BC of interference between neighbouring control zones; and

Figure 6c illustrates a fully coupled multiple input multiple output control system having a signal control zone ABC with six loudspeakers and twelve microphones.

The embodiments of the present invention described hereinafter will be described with reference to the time domain filtered-x algorithm. The present invention is not however so limited and is applicable to any control system with multiple inputs and multiple outputs, particularly any of the filtered-x and filtered error LMS algorithms of the prior art.

Figure 3 illustrates schematically the operations of a filtered-x LMS algorithm in the time domain coupling between a single loudspeaker and a single microphone (i.e. a single response or coupling).

As can be seen in Figure 3, a reference signal x representative of a phenomena affecting the plant P is input to the digital FIR filter W. The digital FIR filter W then filters the reference signal x to generate an input signal to the plant P. The reference signal x is also put through a model filter C which models the response of the plant. The filter reference signal r is then compared with the output error signal e in the least mean square (LMS) algorithm. The LMS algorithm generates an update for the coefficients of the digital FIR filter W in order to adapt the coefficients of the FIR filter W in order to reduce the output error signal e from the plant P.

The update of the coefficients of the digital FIR filter W is carried out in accordance with the algorithm

$$w_{mi}(n+1) = w_{mi}(n) + \alpha \sum_{l=1}^{L} e_l\,(n)\, r_{lm}(n-i)$$

$w_{mi}(n+1)$ = the coefficient for the mth actuator and the ith tap of the FIR filter at the n+1th sample

$w_{mi}(n+)$ = the coefficient for the mth actuator and the ith tap of the FIR filter at the nth sample

α = convergence coefficient

$e_l(n)$ = error signal of the lth sensor at the nth sampling point

r_{lm} = filtered reference signal (x) for the n-ith sampling point using model of response between lth sensor and mth actuator.

This equation is valid for a multiple input multiple output arrangement where each actuator for the plant P is driven by filtering a reference signal x using coefficients w_i, and the total number of

sensors is L and the total numbers of actuators is M.

For the single coupling arrangement shown in Figure 3, the model filter C is a filter of the Jth order. For the multiple input/multiple output arrangement the model filter C will comprise a matrix of coefficients c_{lmj}. The filtered reference signal r is then given by

$$r_{lm}(n) = \sum_{j=0}^{J-1} c_{lmj}\, x(n-j)$$

In the fully coupled multiple input/multiple output filtered-x LMS algorithm the model filter in the frequency domain comprises a full matrix

$$C = \begin{bmatrix} c_{11} & c_{21} & c_{31} & \cdots & c_{l1} \\ c_{12} & c_{22} & c_{32} & \cdots & \cdots \\ c_{13} & c_{23} & c_{33} & c_{43} & \cdots \\ \vdots & & & & \\ c_{1m} & \cdots & \cdots & \cdots & c_{lm} \end{bmatrix}$$

Clearly, in such a fully coupled multiple input multiple output control system considerable processing is required to calculate all of the filtered reference values $r_{lmj}(n)$, particularly in time domain processing when L and M are large.

Thus, in accordance with one embodiment of the present invention, in order to reduce the processing requirements, the least significant couplings comprising entries in the above matrix are ignored,

i.e. set to zero. For example, this may result in the entries in the frequency domain matrix furthest from the diagonal being reduced to zero to provide a modified reduced model filter

$$C_s = \begin{bmatrix} c_{11} & c_{21} & O & \cdots & \cdots & \cdots & O \\ c_{12} & c_{22} & c_{32} & O & \cdots & \cdots & \\ O & c_{23} & c_{33} & c_{43} & O & \cdots & \cdots \\ O & O & c_{34} & c_{44} & c_{54} & O & \cdots \\ \vdots & O & \cdots & \cdots & \cdots & \cdots & \cdots \\ O & \cdots & \cdots & \cdots & \cdots & \cdots & c_{\ell m} \end{bmatrix}$$

This frequency domain matrix represents a partially coupled (or partially decoupled) multiple input multiple output system. In this example the number of actuators M is equal to the number of sensors L and terms nearest the diagonal are considered to represent significant couplings, but this represents a simplified example and in practice the couplings which are determined to be significant need not lie in a distribution close to the diagonal. This will depend on the complexity of the plant. Furthermore, in most systems it is generally beneficial that the number of sensors L is greater than the number of actuators M.

Methods of learning the model filter response C are known in the prior art, for example in EP 0233717 and WO94/09482. The model filter coefficients $c_{\ell m}$ in the frequency domain can be learnt by injecting a test signal and correlated with the phenomena affecting the plant either during an initialisation phase or during

the operation of the control system. Where the plant has a steady response which does not change during control, it is sufficient to learn the model filter coefficients $c_{l\omega}$ in the frequency domain during an initialisation phase. Where the response of the plant changes during the operation of the control system, during operation monitoring of the coefficients $c_{l\omega}$ in the frequency domain is required.

The determination of the significance of the couplings can be determined by monitoring the real parts of the eigenvalues of a matrix derived from C. For example, where C is a matrix of the responses of all of the sensors to all of the actuators, H represents the complex conjugate of the transposed matrix, β is a weighting coefficient, I is the identity matrix and C_s is a matrix formed by setting selected coefficients of C to zero, the real parts of the eigenvalues of a matrix $(C_s^H C_s + \beta I)$ can be monitored. A negative real part of an eigenvalue of the matrix $(C_s^H C_s + \beta I)$ indicates a divergent system (i.e. it is not possible to set the selected coefficients of the C matrix to zero without system instability). The more positive the real parts of the eigenvalues of the matrix $(C_s^H C_s + \beta I)$, the greater the convergence rate of the system (i.e. it may be desirable to set a lower limit on the magnitude of the real parts of the eigenvalues and to recognise that if the real parts are below the lower limit then it is not possible to replace a term in C with a zero without the system becoming too slow in convergence).

It is possible to carry out a procedure whereby the model filter coefficients in C can be selectively ignored whilst monitoring stability in order to determine which are significant. For a plant which is stable, this need only occur during the initialisation

phase but for a plant which varies during control, this process must be continuously carried out to compensate for changes in couplings as the new model filter coefficients are continuously learnt.

A further method of determining which terms in C are the most significant is to reduce the terms in the matrix C one by one to zero to form successive matrices C_s and then monitor the resulting increase of noise detected by the microphones. If there is no noise increase or if the noise increase is within acceptable limits then the changed term can remain at zero, if not then it will have to be maintained at its value.

Whilst the present invention is applicable to multiple input/multiple output control systems which utilise a central controller as in the prior art and as illustrated in Figures 1 and 2, the present invention is particularly suited for application in control systems which utilise decentralised control. Two such systems are illustrated in Figures 4 and 5.

In Figure 4, a plant 20, e.g. the cabin of a vehicle such as an aircraft, is controlled by four separate local controllers. Each local controller 41 outputs a signal to a loudspeaker 60. The output of the loudspeaker 60 interferes with the undesired noise entering the plant 20 from the noise source 10. The residual vibrations are detected by the microphones 70. The signals from the microphones 70 are multiplexed by individual multiplexers 90a to 90h. The outputs of the multiplexers 90a to 90h are transmitted over a communication link 95 under the control of a communication controller 100 to the local controllers 41. The local controllers 41 also receive a reference signal 30 from the noise source 10.

Each local controller 41 in this embodiment only

controls a single loudspeaker 60. Thus, each local controller 41 uses a single set of digital FIR filter coefficients $w_{mi}(n)$ to generate the signal for the loudspeakers 60.

Figure 5 differs from Figure 4 in that local controllers 42 each generate two outputs for two loudspeakers 60. In this embodiment the local controllers 42 will utilise two digital FIR filters W to generate the two outputs for the loudspeakers 60.

In both Figures 4 and 5, the signals output from the microphones 70 are multiplexed by the multiplexers 90a to h. The multiplexing is carried out under the control of the communication controller 100 and can be carried out using any conventional multiplexing technique such as time division multiplexing or frequency multiplexing. This enables the local controllers to select which of the multiplexed signals is utilised in the LMS algorithm to adapt the digital FIR filter coefficients $w_{mi}(n)$.

By these arrangements, since the local controllers 41 and 42 and the multiplexers 90a to h can be provided individually for each loudspeaker 60 and microphone 70, distributed processing is possible and the active control system can be provided in modular form. For instance, in an area having a large number of inputs and outputs, e.g. in a cabin of an aircraft, a controller together with its loudspeaker or loudspeakers and microphones together with their multiplexers can be provided in a module with the intention of controlling a volume within the cabin. Figure 6 illustrates a plant 20 housing three modules A, B and C. Each module comprises two loudspeakers and four microphones together with their associated

local controller and multiplexers.

Figure 6a illustrates a fully decoupled system wherein there is considered to be no interaction between the modules. This is however a situation which is very rare and there is likely to be coupling between the modules. Figure 6c illustrates a fully coupled system where each loudspeaker is considered to affect each microphone. Figure 6b illustrates schematically the partially decoupled (or partially coupled) modular system in accordance with one embodiment of the present invention. In this arrangement three modules A, B and C each interact with their nearest neighbour. Thus there is a zone of control AB and a zone of control BC where there is deemed to be interaction. Couplings between loudspeakers and microphones of different modules in these zones of interaction need to be taken into account.

It will readily be seen from the simple schematic diagram of Figure 6b that such a modular active noise control system as provided for by one embodiment of the present invention can provide for a flexible control system allowing for the configuration of the control system to be changed. For example in an aircraft, each of the modules A, B and C may be associated with for instance a seat in the aircraft. If it is desirable to modify the seating arrangement in the aircraft, the active control system can be modified simply by plugging and unplugging modules associated with the seats. The system can then learn the important couplings either during an initialisation phase or during the operation of the active control system.

All the present invention has been described hereinabove with reference specific embodiments, and

it will be readily apparent that the present invention is not so limited. It will be recognised that various equivalents, alternatives and modifications are possible within the scope of the appended claims.

CLAIMS

1. An adaptive control system for controlling a plant comprising a plurality of actuator means for controlling said plant; a plurality of sensor means for sensing the degree of success in controlling said plant; and actuator control means adapted to control each said actuator means in response to selected ones of said plurality of sensor means, said selected ones being some and not all of the said plurality of sensor means, said actuator control means being adapted to select said selected ones of said sensor means by considering couplings between each said actuator means and each said sensor means and determining which couplings are the most significant.

2. An adaptive control system as claimed in Claim 1 including reference means adapted to provide an indication of at least one parameter of a phenomenon affecting said plant, wherein said actuator control means is responsive to said reference means.

3. An adaptive control system as claimed in Claim 1 or Claim 2 including test signal generating means for generating a test signal for each said actuator means, wherein said actuator control means is further adapted to select the selected ones of said sensor means for each of said actuator means by determining the significance of signals produced by each of said sensor means in response to outputs of each of said actuator means occasioned by the test signal.

4. An adaptive control system as claimed in any preceding claim wherein said actuator control means is further adapted to determine which couplings are

significant by monitoring the real parts of eigenvalues of a matrix derived from the response of each of said sensor means to each of said actuator means.

5. An adaptive control system as claimed in Claim 4 wherein said actuator control means is adapted to determine which couplings are most significant by monitoring the real parts of the eigenvalues of a matrix $(C_s^H C_s + \beta I)$, H denotes a complex conjugate of a transposed matrix, β is a weighting coefficient, C_s is a modification of a matrix C with selected terms of the matrix C set to zero, the matrix C is a matrix of the responses of each of said sensor means to each of said actuator means, and I is the identity matrix.

6. An adaptive control system as claimed in claim 5 wherein the significance of a coupling is determined by reducing to zero in the matrix C a term or terms which represent the coupling to form the matrix C_s and then determining the change in the real parts of the eigenvalues of the matrix $(C_s^H C_s + \beta I)$.

7. An adaptive control system as claimed in claim 6 wherein the coupling is determined to be significant if a real part of an eigenvalue of the matrix $(C_s^H C_s + \beta I)$ becomes negative when the term or terms representing the coupling in matrix C is/are reduced to zero.

8. An adaptive control system as claimed in claim 6 or claim 7 wherein the coupling is determined to be significant if the magnitude of a real part of an eigenvalue of the matrix $(C_s^H C_s + \beta I)$ decreases below an acceptable limit when the term or terms

representing the coupling in matrix C is/are reduced to zero.

9. An adaptive control system as claimed in any one of claims 1 to 3 wherein a coupling is determined to be significant by ignoring the coupling and then deciding that the ignored coupling is significant if ignoring the coupling leads to an decrease in the degree of success sensed by the sensor means and the decrease in the degree of success is greater than a preprogrammed limit value.

10. An adaptive control system as claimed in any preceding claim wherein said actuator control means comprises a plurality of local actuator controllers, each said local actuator controller controlling one or a group of said actuators.

11. An adaptive control system as claimed in Claim 10 wherein the number of said actuator means and said sensor means can be increased or decreased; each said local actuator controller being adapted to reselect said ones of said sensor means when the number of said sensor means is changed.

12. An adaptive control system as claimed in Claim 2 wherein said plant comprises an acoustical system, said reference means provides an indication of at least one parameter of an acoustical signal affecting said plant, said actuator means comprises output transducer means, and said sensor means comprises input transducer means.

13. An adaptive control system as claimed in any one of Claims 1 to 9 wherein said actuator means and said

sensor means are divided into a plurality of local groups of actuator means and sensor means; said actuator control means comprising a plurality of local actuator controllers; each local actuator controller controlling the actuators of a respective local group and each local actuator controller being responsive to all the sensor means of the respective local group and each local actuator controller being responsive to selected ones of sensor means of other said local groups, the selected ones of the sensor means of the other said local groups being some and not all of the sensor means of the other said local groups.

14. An adaptive control system as claimed in Claim 13 wherein the number of said local groups can be increased or decreased; each said local actuator controller being adapted to reselect said ones of said sensor means of said other said local groups when the number of said local groups is changed.

15. An adaptive control system as claimed in any preceding claim wherein said actuator control means is adapted to select said selected ones of said plurality of sensor means by learning which are necessary to represent the most significant of the couplings during an initialisation phase of said system.

16. An adaptive control system as claimed in any preceding claim wherein said actuator control means is adapted to select said selected ones of said plurality of sensor means by learning which are necessary to represent the most significant of the couplings during the operation of said system.

17. An adaptive control system as claimed in Claim 16

including test signal generating means for generating a test signal uncorrelated with any phenomenon affecting said plant for each said actuator means, said actuator control means being adapted to select said selected ones of said sensor means for each said actuator means by determining the significance of signals produced by each said sensor means in response to outputs of each of said actuator means occasioned by the test signal.

18. An adaptive control system as claimed in any preceding claim wherein said actuator control means adaptively controls said actuator means in accordance with a least mean square algorithm based on the responses of each of said selected ones of said sensor means.

19. An adaptive control system as claimed in any one of Claims 10, 11, 12, 13 or 14 wherein each said local actuator controller is electrically connected to each said sensor means by a communication link, each said sensor means including multiplexer means adapted to multiplex signals generated by said sensor means for transmission by said communication link.

20. An adaptive control system as claimed in Claim 19 wherein each said multiplexer means is adapted to transmit a said signal during an allocated period during a cycle, said cycle representing at least the time taken for all said multiplexer means to transmit said signals.

21. An adaptive control system as claimed in Claim 9 wherein each said multiplexer means is adapted to digitize said signal and transmit digitized signals at

allocated time intervals such that digitized signals from respective said multiplexers are interleaved when transmitted over said serial link.

22. An adaptive control system as claimed in Claim 19 wherein each said multiplexer means is adapted to modulate a respective carrier frequency with said signal, said serial link being adapted to transmit said signals from said sensor means as frequency multiplexed signals comprising a plurality of said carrier frequencies modulated by respective said signals.

23. An adaptive control system as claimed in any one of Claims 19 to 22 including communication control means adapted to be linked to each said multiplexer means and to control the transmission of signals over said communication link.

24. An adaptive control system as claimed in any one of Claims 19 to 23 wherein each said local actuator controller includes demultiplexer means to demultiplex the signals transmitted over said communication link to enable said selected ones of said sensor means to be determined.

25. An adaptive control system as claimed in any one of Claims 19 to 24 wherein said communication link comprises a digital bus having a plurality of lines for the transmission of signals, and one or more lines for the control and timing of the transmission of signals.

26. An adaptive control system as claimed in any one of Claims 19 to 25 wherein each said sensor means and

each said local actuator means include receiver means and transmitter means arranged to serially receive and transmit respectively radiation modulated by respective said signals.

27. An adaptive control system as claimed in Claim 2 wherein each said actuator control means comprises at least one digital adaptive FIR filter for filtering at least one reference signal derived from said reference means.

28. An adaptive control system as claimed in Claim 27 wherein said actuator control means includes a model filter which models the response of each of said selected ones of said sensor means to an output of each of said actuator means, and said digital adaptive FIR filter is adapted using a filtered-x algorithm, where said model filter is used to filter a reference signal x derived from said reference means.

29. An adaptive control system as claimed in Claim 27 wherein said digital adaptive FIR filter has a plurality of coefficients w_{mi} for the control of each said actuator means, said adaptive digital FIR filter being operative to be adapted every sample n according to the equation:

$$w_{mi}(n+1) = w_{mi}(n) + \alpha \sum_{l=1}^{L} e_{lm}(n)\ r_{lm}(n-i)$$

where m denotes one of the actuator means and i is an integer which denotes the number of tap of the FIR filter, α is a convergence coefficient, l denotes one

of said selected ones of said sensor means, L is the total number of said selected ones of said sensor means determined to be important, $e_{lm}(n)$ denotes the sampled response of a selected one of said sensor means, and $r_{lm}(n-i)$ denotes a modified reference signal formed by filtering a reference signal from said reference means using a model filter which models the response of the l^{th} said selected one of said sensor means to an output of the m^{th} actuator means for which control is occurring using w_{mi}.

30. An adaptive control system as claimed in Claim 29 wherein said actuator control means is operative to determine:

$$r_{lm}(n) = \sum_{j=0}^{J-1} c_{lmj}\, x(n-j)$$

where c_{lmj} is said model filter which models the response of the l^{th} selected one of said sensor means to the output of the m^{th} actuator means, j is the filter coefficient, and x(n-j) denotes the sampled reference signal.

31. An adaptive control system as claimed in Claim 27 wherein said digital adaptive FIR filter operates in the frequency domain and has complex filter coefficients and said actuator control means includes model filter means comprising complex filter coefficients which model the transfer function between each of said actuator means and the selected sensor means selected for each actuator means, said digital adaptive FIR filter being operative to filter said reference signal to generate drive signals for each of

said actuator means, and to be adapted in response to either a combination of said reference signal and output signals from said selected ones of said sensor means filtered by the complex conjugate of the filter coefficients of said model filter means, or a combination of output signals from said ones of said sensor means and said reference signal filtered by the filter coefficients of said model filter means.

32. An adaptive control system as claimed in Claim 27 wherein said actuator control means includes model filter means comprising coefficients which model the response of each of said selected ones of said sensor means to each of said actuator means, said digital adaptive FIR filter being adapted in response to the correlation between said reference signal delayed by a predetermined amount and output signals from said selected ones of said sensor means filtered by filter coefficients of said model filter means in time reversed order.

33. An active control system as claimed in Claim 16 wherein said actuator control means includes test signal generating means for generating at least one test signal to be added to output signals of said actuator means, said test signal being uncorrelated with a phenomena affecting said plant, said actuator control means being adapted to compare said test signal with signals from all of said sensor means to determine the most significant couplings.

34. An active control system as claimed in Claim 33 wherein said sensor means produce at least one error signal and said actuator control means comprises a digital adaptive FIR filter for filtering at least one

reference signal representing a phenomenon affecting said plant, and a model filter which models the response of each of said sensor means to an output of each of said actuator means, said digital adaptive FIR filter operating in the time or frequency domain and being adapted using a filtered reference or a filtered error algorithm, and wherein filtering of the reference signals or the error signals is carried out by coefficients of said model filter representing the most significant couplings, said model filter being responsive to said comparison to learn the response of all of said sensor means to an output of each of said actuator means, the system including matrix monitoring means for monitoring the real parts of eigenvalues of a matrix derived from the coefficients of said model filter to determine which of the responses represent the most significant couplings.

35. An active control system as claimed in claim 34 wherein the system determines a significant coupling by replacing the coefficient(s) relating to that coupling by zero(s) then monitoring the changes in the real parts of the eigenvalues of the matrix derived from the coefficients of the model filter.

36. An active control system as claimed in Claim 35 wherein said digital adaptive FIR filter and said model filter operate in the frequency domain, said model filter being operative in response to said comparison to only modify coefficients thereof at frequencies not in said reference signal and at which said digital adaptive FIR filter is not working.

37. An adaptive control system substantially as hereinbefore described with reference to any of the

drawings.

The Patent Office

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Claims searched: 1 to 37

Examiner: John Donaldson
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Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:
UK Cl (Ed.O): G3R(RBC25, RBC29, RBS, RBU); G3N(NGBA, NGBA3, NGE2); H4J(JGA)
Int Cl (Ed.6): G05B 11/00, 11/01, 11/06, 11/32, 13/00, 13/02, 15/00, 15/02; G10K 11/00, 11/16, 11/175, 11/178
Other: Online: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	GB 2259223 A (NISSAN), see abstract	-

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